

<p>Contract N°: BRE2-CT92-0258</p> <p>Project N°: BE 5621 -92</p>	<p>Project Title:</p> <p>KERNEL</p> <p>for Advanced Machine Tools</p>	<p>Partners:</p> <p>COMAU FIDIA CNR-ITIA G E C ALSTHOM K. U. LEUVEN SCHNEEBERGER</p>
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SYNTHESIS REPORT

TITLE: *KERNEL for Advanced Machine Tools*

Project Coordinator: **COMAU SpA**

Partners involved:

- FIDIA SpA**
- CNR - ITIA**
- GEC ALSTHOM PARVEX**
- KATHOLIEKE UNIVERSITEIT LEUVEN**
- W. SCHNEEBERGER AG**

Availability: For Publication

Reference period: From 01.11.1992 to 01.03.1995

Duration: 28 Months



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Partnership : COMAU (C), Fidia (P), CNR-ITIA (P), Gec Alsthom Parvex (P), K.U. Leuven (P), W. Schneeberger (P).

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1 ABSTRACT

KERNEL, the subject of this synthesis report, deals with the design of the motion control unit for machine tools of the next generation, by use of the most advanced design techniques. The analysis has been focused on machine tools belonging to Domain of Analysis (D.o.A.), characterized by low working forces, high speed and acceleration, medium/high precision, medium working volume. Within this domain, the typical machines are drilling machines, machining centres, milling machines, transfer line modules, and so on. Among the several architectures and fictional components, a limited subset has been chosen. Object of the research was, in fact, the development of the functional units M.C.U (Motion Control Units), made up by the selected components. Within the overall project, it is possible to identify the following areas of high importance and interest:

- Architecture analysis and modularity
- Structures and Materials
- Tribology problems
- Kinematic chains
- Motors, Drives and Advanced Control Techniques
- Study of suitable simulation environments for computer aided design of machine tools

Within KERNEL, a consortium, consisting of COMAU (main partner) (I), FIDIA (I), CNR-ITIA (I), GEC ALSTHOM (F), PMA-K.U.LEUVEN (B), SCHNEEBERGER (CH), have worked closely together during two years and have produced a set of results which prove that the goals, set out at the beginning of the project, can be reached. Two benchmark systems were defined by the industrial partners: a drilling unit (COMAU), where the main aim is a reduction of positioning time, and a high-speed milling unit (FIDIA), where small contouring errors at high feedrates are of paramount importance.



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2 INTRODUCTION

Around 1990, the EC launched uninteresting initiative in an attempt to safeguard the future of the European machine-tool industry against the outside, particularly Japanese, competition. A working group, including representatives from the machine tool industry and academia, was put together and the activities of the group resulted in the so called CEDAM (Concurrently Engineered Design Approach of Machine Tools)-concept.

The rationale behind the CEDAM-approach was that the present European machine-tool industry, with its thousands of small companies, manufacturing thousands of different types of machine tools, cannot survive into the 21st century if it maintains its present structure. The individual companies can impossibly continue to bear the enormous R&D costs involved in the development of modern machine tools. On the other hand, although the turnover of the 'machine-tool industry is relatively small in absolute figures, it is a strategic industry sector which Europe cannot afford to abandon. Therefore, the CEDAM working group came with the proposal to design and build machine tools in a completely modular way. Individual companies would then specialise in the manufacture of single modules. System integrators would design and integrate complete manufacturing systems by combining different modules in order to satisfy customer specifications.

Already in 1992, the first BRITE/EURAM-projects along the lines of the CEDAM-ideas were launched. Logically, the first project, called MAREA (Study and definition of MACHining workstation REference Architecture), had to do with generic ideas on how a system architecture for a modular machine tool should look like. Simultaneously with MAREA, a few projects were launched on the development of particular modules, like the motion control unit, the spindle unit; bearings and guideways, The KERNEL-project, described in this report, is one of those module-projects. In the fourth framework, the CEDAM-philosophy will be further developed and meanwhile new project proposals are being formulated.

This report synthesizes the main achievements of the project. Details can be found in the numerous reports produced as deliverables during the project and a list of which can be found in References. In the next chapter the technical description is organized according to the following:

- *Architectures of machine control units according to the CEDAM-approach;*
- *Structural and Material aspects;*
- *Tribological aspects;*
- *Kinematic Chains;*
- *Motors, Drives and Advance Control System;*
- * *Design Tool ad Methodologies for the Machine Tool industry.*

At the end, the main achievements of the KERNEL project are summarised.

3 TECHNICAL DESCRIPTION

This chapter gives a technical description for each of the above listed main tasks of the project.



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3.1 Architecture of Machine Tools according to the CEDAM approach

The architectures for the M. C.U.'s have been studied according to the CEDAM approach. CEDAM introduced from the beginning the concept of "reference architecture" giving the following definition:

"The meaning of a reference architecture is a generic model where a clear definition is given of the fictional units and the interfaces with the external components. The reference architecture would thus provide a central, clearly understood basis to which all could refer." (See CEDAM document March 1993).

In the same document, the following starting ideas were given to elaborate the concept of reference architecture:

- A purely hierarchical (physical) decomposition approach (figure 3.1)
- A more fundamental and general approach (Functional decomposition approach) (figure 3.2) consisting of:
 - an analysis of the **different functionalities** of machine tools types (e.g. the fictions of the feeding material, cutting material, removing material, . . .)
 - a definition of the requirements for each of these **functionalities** (speed, accuracy,....);
 - a study of fictional components, **fulfilling** these requirements;
 - an identification of functional units that is applicable to several machine tools and more dedicated functional components;
 - an identification of the **crucial interfaces** between the fictional units.

Considering that the KERNEL project:

- is oriented towards the study of high performance machine tools,
- refers to the CEDAM concept of the machine tool industry

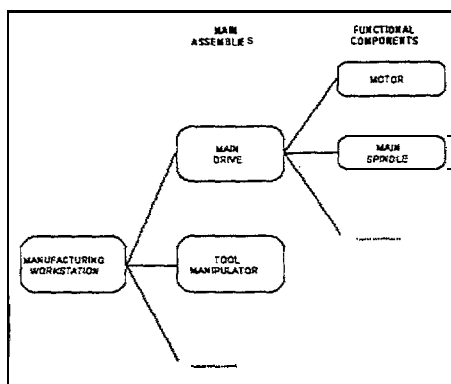


Figure 3.1 Technical decomposition

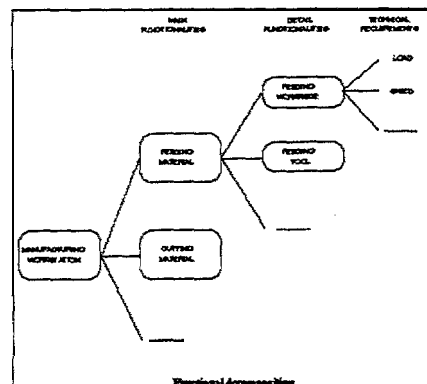


Figure 3.2 Functional decomposition

the profile of the envisaged technical reference requirements of KERNEL, demand a significant technological jump. The percentage of performance increase varies from a minimum 60% up to a maximum 1000% compared to the actual machine tools.

The level of performance required cannot be reached by means of a simple incremental improvement of the actual products. Rather, it needs a substantial revision of the conception and implementation processes of the machine tool, allowing the integration of innovative design technologies and solutions.



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To reach such objectives in the KERNEL project, here follows a list of activities developed for the machine tools within the "Domain of Analysis" (the D. o.A machines):

1. Analysis of current architectures of D.o.A. machines through a Functional Analysis Method

The aim was to define in detail the typology of the state-of-the-art machine in the D.o.A. Through a deep study of the current architectures of the D.o.A., recognition and definition of further Functional Units have been carried out.

2. Study of Motion Control Units (M.C.U.) architectures and their development

This second activity considered the definition of the possible architectures that the M.C.U. (units which perform all feed and positioning motions except for the movements contained in the technological operator) would assume to satisfy the specific needs deriving from specific envisaged performances.

3. M.C.U. interfacing problems analysis

This third activity studied the different interfaces: positioning, mechanical with coupling, mechanical with blocking, electronic, electrical power, hydro-pneumatic power. Such interfaces will guarantee the solution of safety problems and environmental pollution to obtain proper working conditions.

Objectives of this activity have been fully reached. The proposed set of "Functional Units" has been verified as in accordance with the requirements of the KERNEL project and provides a reference architecture for the machines of D.o.A. Key aspects for the definition of the architecture for the Motion Control Unit have been analysed.

In order to provide more specific design prescriptions, a bottom-up procedure has been identified, based on the analysis of design aspects. The proposed approach is therefore strictly related to the development of a design environment in which the technical analysis of main design issues can be carried out .

3.2 Structure and Materials aspects

The use of innovative materials in machine tools can answer the market need for faster and more accurate machines. In particular, the use of materials that allow a reduction of the structural weight without losing stiffness, is the first step to reach high performances without over-dimensioning the other components of the M. C. U.(drives, engines, ball screw, . . .).

Traditionally, steel and cast-iron are used in machine tools. It is possible to achieve good results with these materials. With software in the design field (CAD, CAE, . . .). it is possible to re-evaluate the traditional material in order to make the optimal use.

The application of new materials is limited, due to the cost, to the lack of documentation and information and for a sort of reluctance of the buyers. The research activity started with an examination of the existing industrial application in order to better understand the advantages and problems deriving from possible new solutions.

The final objectives of the project activities were:

- collection of design criteria for existing machines;
- collection of information on materials for possible use in the structure of a new generation M. C.U.;
- proposal for alternative structural solution.



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Starting from solutions adopted in parallel sectors to the machine tool sector, like the laser machines, or even the aeronautic sector, it is possible to achieve at new materials and innovative structural solutions to allow high performances.

The design has to be completely reconsidered to find new structure forms that can properly employ the materials, and can solve the interfacing problems that arise when non-traditional drive systems (linear motors, active dampers. ..) are used.

Among the proposed solutions, we have studied the feasibility of the following:

- for the Fixed parts the realisation with polymeric elements (possible internal metallic frame) of the bed of a M. C. U.;
- for the Moving parts:
 - welded structures of a M.C.U. with thin walls + plastic fillings (concrete) and possible integration with sandwich structures (honeycomb);
 - realisation of moving parts (ram) with advanced composites.

The obtained results bring to the following considerations:

- the foreseen structural solution for the new generation M.C.U. gives good results, even through it involves the problem of using different and new techniques (it is necessary to use traditional materials in an innovative way);
- the real benefits of the use of composites result if the weight of the whole machine is optimized; that means not only to reconsider the structural components but to study a better integration with the other M. C.U.'s components (electrospindle, guideways, ..).

3.3 Tribological aspects

As Motion Control Units, slideways play a significant role in determining the accuracy, speed and controllability of a machine tool, as far as they are accurate, low-friction, stiff and well-damped respectively. Unless the positioning errors of a machine are measured and (by some means) compensated, accuracy can only be guaranteed by geometrically accurate slideways. Wear or distortion of the slide or the guideway will mean a degeneration of that accuracy. Friction may lead to certain types of unstable behaviour at low speeds, and to the generation of heat, at high speeds, which causes distortion of the geometry of the machine thereby limiting the maximum allowable speeds. Certain types of fiction are preferred to others, but low friction is generally considered as a favorable characteristic.

Controllability of a machine tool is associated with the stability of the motion of the component parts, and consequently with the stiffness and the damping of the motion, both in the longitudinal and the transverse directions.

Different types of slideways are available. They may be divided into a number of principal types from which other sub- or hybrid types may be derived. The division is best made on the basis of their operation principle or mechanism. All of the different types of slideways are to be found in applications compatible with their relative capabilities, (different types are to be often found in the same machine).

Following the CEDAM approach, the various slideway technologies are considered, in principle, equally valid in the framework of the KERNEL project in as far as they could meet the desired performance requirements. In particular, two aspects are considered to be of special importance, namely *modularity* and *the potential for active control*.

A comprehensive study is therefore necessary if a proper selection of slideways is to be envisaged.

After providing an overview of the present state of the art in slideway bearing systems, this study has followed two main lines, The first is related to recent developments in actuator and control technology



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and its impact on bearing systems, namely the implementation of active and semi-active compensation of bearing force, and consequently the system's dynamics.

Although this possibility has a great potential, (and should therefore be further pursued) it is not yet economically viable on account of the hitherto high component cost. The second line of investigation treated the basic problems of a topical, modular slideway technology, viz., recirculating rolling element guideways. The problem of modelling, design and implementation of squeeze film dampers into such guideway system (in order to increase their otherwise poor damping) has been thoroughly treated. The second basic problem is that of friction behaviour and control. Both pre-rolling and post rolling friction have been experimentally identified.

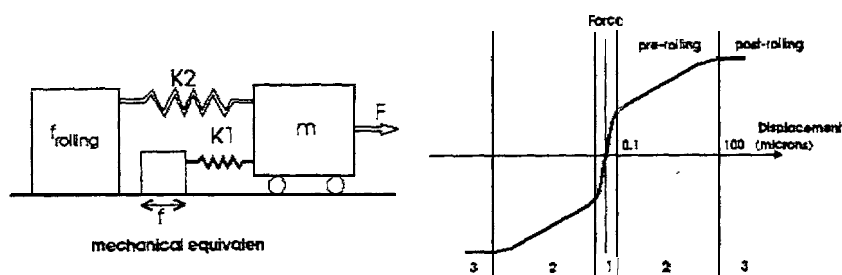


Fig. 3.3.1 Pre-rolling friction behaviour and its simplified non-linear spring equivalent

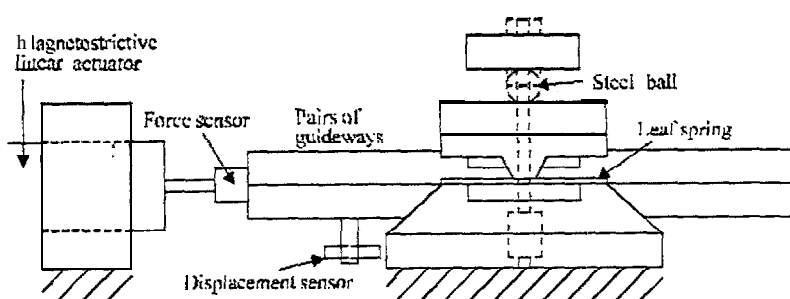


Fig. 3.3.2 Test set-up for evaluation of pre-rolling friction in a monorail

The first type has been modelled and simulated so that effective controllers may be designed to overcome the (quadrant) tracking errors caused by this friction phenomenon. The possible causes of the stochastic character of rolling friction have been identified and effective design measures have been taken to overcome them as well as to reduce the mean value of the friction force.

3.4 Kinematic chains

The aim of the activity was to evaluate the feasibility of traditional solutions (rack and pinion, ball rolling screw) for high performances machines, with respect to the availability of commercial componentry. The possibility of the use linear motor has also been considered.

The feasibility analysis of these solutions has been made for a new generation of machines, characterised by "exceptionally high" performances, of particular interest for Fidia and COMAU.

Fidia is interested in high speed machines for the production of dies. These machines have to be more and more versatile and able to carry out an increasing number of operations, like:

- geometric test of die surfaces, with continuous reading and fast point-to-point techniques;
- continuous digitizing techniques of model surfaces, with laser or electromechanical feeler;



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- high speed milling of models;
- high speed milling of graphite or chipper electrodes;
- very high speed superfinish milling of die surfaces.

COMAU, that produces Flexible Transfer Lines (FTL) for the automobile industry, has to cope with a market, searching for new solutions to obtain more and more qualified and differentiated products. Although FTL is traditionally used for low differentiation mass production, there is a trend towards solutions more suitable for the production of different parts of the same family with batches of different size. To satisfy this request, in some production lines the multispindle units are going to be replaced by high performance monospindle units, easier to be reprogrammed. They have to be used in production processes with high cadence per hour (about 200 cycles/hour).

Based on the market trend and on the experience from the industrial partners, the parameters of two machines of a new generation have been defined:

- a polyfunctional machine for dies (milling at high speed, measuring and digitising)
- a machine for drilling and tapping for FTL

Tab. 3.4.1 Drilling and tapping machine for FTL (Flexible Transfer Line)

	X-axis	Y-axis	Z-axis
mass	800 kg	400 kg	110 kg
velocity	120 m/min	120 m/min	120 m/min
acceleration	20 m/sec ²	20 m/sec ²	20 m/sec ²
positioning accuracy	10 µm	10 µm	10 µm
stabilisation time	50 msec	50 msec	50 msec
stroke	500 mm	500 mm	500 mm

Cutting force = 2000 N.

Tab. 3.4.2 Polyfunctional machine for dies (for fast milling, measuring and digitizing)

	X-axis	Y-axis	Z-axis
mass	400 kg	300 kg	100 kg
velocity	60 m/min	60 m/min	60 m/min
acceleration	15 m/sec ²	15 m/sec ²	15 m/sec ²
tracking accuracy (v=30m/min)	10 µm	10 µm	10 µm
measuring accuracy (v=3m/min)	1 µm	1 µm	1 µm
stabilisation time	30 msec	30 msec	30 msec
stroke	1000 mm	600 mm	500 mm

Cutting force in milling= 600 N

A market study for the high performance machines in the D.o.A., confirmed that the most frequently used kinematic solution is ball screw; only few machine uses linear motors.

Figure 3.4.1 gives an overview of the maximum speed of the machines from the market study.



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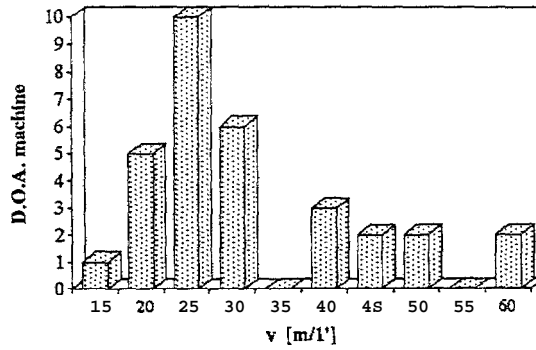


Figure 3.4. 1 Comparison of velocity of machine from the market study

For instance the COMAU “lg” machine can reach already a velocity of 60 m/min and an acceleration of 10m/sec², using a long thread ball screw as kinematic solution.

COMAU proposed a machine based on a new conception. On the basis of the parameters defined for the new generation machine, the study of the kinematic chain was focused on one axis of that machine, namely the X-axis, that puts the most severe conditions on the kinematic chain. At first the use of the traditional solutions, namely the ball screw and the a rack-pinion, has been considered. For every possible solution the axis design has been optimised in order to compare the simulation results.

The envisaged performances has been chosen starting from the actual specifications of the COMAU “lg” machine (a= 10 m/sec² and v= 60 m/min).

The time gain in a position cycle has been evaluated by increasing velocity and acceleration, taking into account that every effort in improving performances always means extra cost of the machine components (motor, ball screw, guideways, structure, ...).

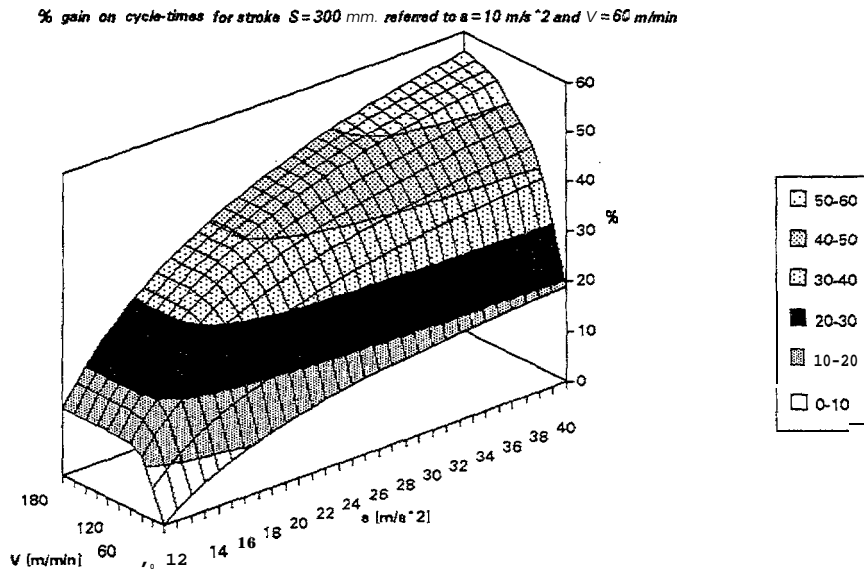


Figure 3.4,2 Gain in cycle time versus increase in velocity and acceleration



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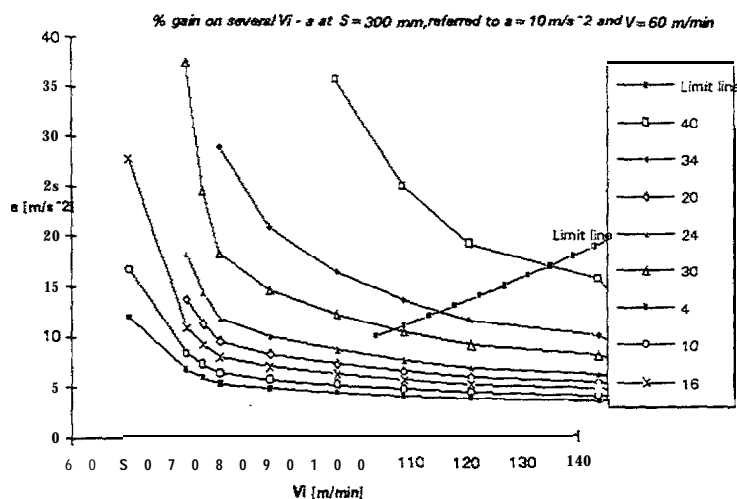


Figure 3.4.3 Gain in cycle time versus increase in velocity and acceleration

The specifications of the machine to be developed should be:

$$a = 20 \text{ m/s}^2,$$

$$v = 120 \text{ m/min}.$$

The conclusion was that the traditional solutions (ball screw, rack and pinion) cannot achieve the target performances: an M.C.U. with a weight of 800 kg, $v = 120 \text{ m/s}$, $a = 20 \text{ m/s}^2$ because of their limitations (maximum achievable speed and short life for ball rolling screws, motion irregularity due to friction for rack and pinion). For these reasons the innovative solution of linear motors has been studied.

Generally, the linear motor design has the following advantages over the rotary motor design:

- no friction and no back-lash, which allows very high accuracy
- no mechanical transmission unit and thus high acceleration and velocity possible
- dynamics are only limited by encoder resolution measurement noise and the calculation time
- mechanical simplicity and higher reliability.

The linear motor solution gives also a better accuracy and repeatability, principally due to the precision of the transducer system. The absence of the stiffness of the kinematic chain allows to obtain a higher bandwidth of the servo system.

On the other hand the use of linear motors needs a non conventional design to obviate the undesired effects as:

- motor ripple;
- no absolute measurement device and thus difficult motor phasing at start;
- high attraction force;
- big contact surface of motor with machine tool body: water cooling necessary;
- synchronous motor: high price (of magnets);
- modified synchronous motor: high mass;
- large overall dimensions.

All these aspects have been considered in the design of the new generation machines.



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3.5 Motors, Drives and Advanced Control System

The selection of the actuator principle is a crucial choice in the M.C.U. design.

The **servodrive** is probably the most difficult subsystem of a motion control system to design and is the most critical to the system performance.

In close collaboration with Comau and Fidia, two typical drive systems belonging to typical machine tools, of particular relevance to these partners have been selected: the *polyfunctional machine* (milling at high speed, measuring and digitizing) and the *drilling and tapping machine for flexible transfer line* (chapter-3.4).

The evolution in production techniques (e.g. high-speed milling) and the required shortening of the production cycles, impose more stringent requirements on the velocity and acceleration of the machine tool axes. Along with the higher speeds, also the requirements on machining accuracy are increasingly more stringent. At these high working speeds (e.g. 30m/min feedrate for high speed milling), the desired accuracy can not be attained by traditional control techniques. Model-based control techniques must be applied in order to meet the conflicting requirements of higher speed and accuracy.

The possibility to reach the target performances of the two cases studies has been considered by means of simulation and test activities on scale models of the case study axes.

Simulation activities:

Each axis was simulated on the GecAlsthom system simulator in order to evaluate the performances of the speed and position loop. Therefore, the drive and NC settings have been optimised. Each axis has been analysed to evaluate the low speed movement quality and the actual axis stiffness with drive and NC.

This activity has brought the following considerations for feed drivers actuators.

Rotary motors: the requirements can be satisfied with rotary motors available on the market except for the X-axis of the fast drilling machine, where a new low inertia motor is required. On this particular axis, a dual motor solution must be envisaged. The movement quality requirements can be met with rotary motors.

Linear motors: in the case of linear motors, several design parameters have to be improved to approach the movement quality goals. These parameters are the motor force ripple and the effect of attraction force variation. The actual state of the art of linear motors is not sufficient to obtain the desired motion quality.

A preliminary design of a 10,000 N linear motor has been made to assess the feasibility of its use in the case studies put forward by COMAU.



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Drives: the chives should be digital drives able to integrate feedforward algorithms and torque prediction. This is required in order to allow fast stabilisation times and to reduce tracking errors during the movement.

Test activities:

At the KULeuven three test set-ups have been used to compare the behaviour of the traditional axis design (rotary motor with ball screw) and the linear motor axis and to test the possible performances with advanced control algorithms.

- * maximum speed: 2m/sec
- maximum acceleration: 20m/sec²
- sensor resolution: 1pm
- sensor accuracy: 3pm
- controller board: DSP-C31

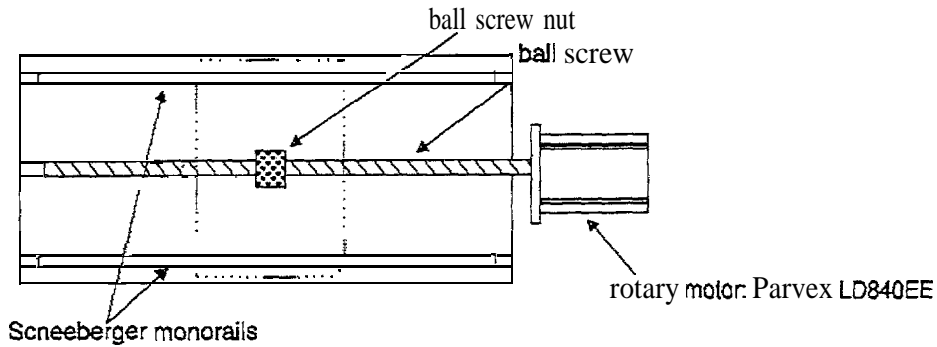


Figure 3.5.1 The rotary motor axis

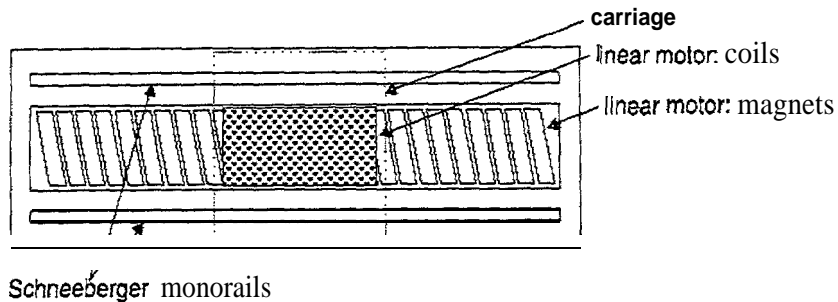


Figure 3.5.2 The linear synchronous motor axis on monorails.



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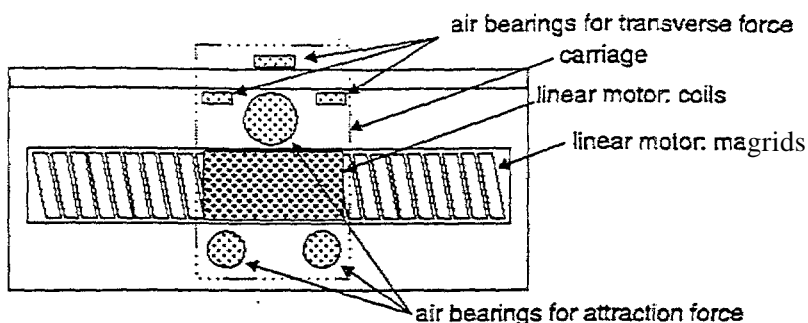


Figure 3.5.3 The linear brushless DC motor axis on air bearings

For the rotary motor the controller was characterized by state feedback and feedforward, while for the linear motor the controller was based on feedback, ZPETC feedforward, a disturbance observer and a reference state generator.

The most outstanding result of these tests was that the tracking accuracy of a machine tool axis can be remarkably increased by the use of advanced control techniques.

For instance, in the case of linear motor, "when state feedback, ZPETC (Zero Phase Error Tracking Control) feedforward, disturbance observer and reference state generator are applied together, the resulting steady-state positioning error is approximately zero. The maximum tracking error is reduced to 30µm (Fig. 3.5.4). The oscillation appearing in the tracking error is due to the motor ripple of the magnets of the linear motor. This error can only be removed adequately by a non-linear controller, based on a good knowledge of the disturbance forces.

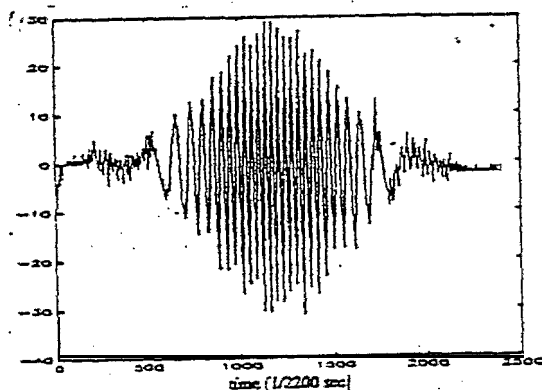


Figure 3.5.4 State feedback + feedforward + disturbance observer + reference state generator: tracking error

A special feedforward scheme for force ripple compensation in the linear motor system has been also added: it resulted in a tracking error reduction by a factor of three.

The algorithms were also implemented in a Motorola based Fidia CNC, set up on a Cortini M500 milling machine. Several tests were made, which have undeniably pointed out a remarkable improvement of the accuracy (up to 5 times better than with traditional controls!).



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3.6 Design tool and methodologies for the machine tool industry

This activity aimed to evaluate of design tools and methodologies for use in the machinetool design, in order to set up a simulation environment tailed “mechatronic compiler”. With such simulation environment an integrated multi-disciplinary machine tool model has been developed in order to study the relationship between component and machine performance.

The aim was to provide and test specific tools for the design of high performance Motion Control Units, following the scenario proposed in the CEDAM report, i.e. specialised constructors of dedicated modules.

The work started from the analysis of the state-of-the-art technologies. Then it was necessary to identify the most suitable simulation environments, in order to achieve the best results in the design of D.o.A. machines. Each tool was tested and compared with the other, in order to set off advantages and flaws, and the trade-off involved in the choice of one instead of another. Finally, a complete integration of all selected tools was carried out. The analysis performed on the available simulation packages led to the choice of three classes of environments:

- environment for control design
- environment for multibody dynamic simulations
- environment for finite element analysis

A software interface was produced to import flexible mechanical components from FEA to multi-body packages.

The final model of drilling machine was used to investigate the contribution of structure, guideways and control to system damping at the various operating frequencies. It was also possible to simulate the execution of a positioning command, taking into account the structure dynamics and the control dynamics; the same model would be useful to evaluate, in the design phase, a controller using modern control techniques that need a model of the machine.

4 CONCLUSION

The KERNEL project produced interesting results, some of them directly applicable, other leading to an enhanced insight in physical phenomena and in the way how motion control modules for machine tools can be designed for optimum performance. An overview of the *main* results is given hereafter.

1. An architectural framework has been worked out to define the architecture of Motion Control Units for machine tools according to the CEDAM-approach. This framework provides a systematic approach, in the conceptualisation phase, to translate the needs of the user or the machine tool builder into objective fictional requirements.

2. The feasibility of using alternative materials and/or structural shapes for the (Motion Control Units) of machine tools has been studied. Possible alternative materials are: fibre-reinforced composites, thin-walled welded structures with plastic filling, eventually combined with sandwich structures. It turned out that important weight reductions are feasible compared to traditional solutions, but that shape optimisation should be considered simultaneously, in order to achieve sufficient (static and dynamic) structural stiffness values.



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3. A comparative study into the different slideway technologies and their underlying tribological principles has been carried out in addition to the investigation of new and hybrid techniques in bearing and damper design which allow for active, on-line, compensation of slideway dynamics. Particular attention has been paid to friction identification modelling and improvement/compensation, in rolling element slideways, leading to significant results,

4. A comparative study of ball-screw, rack-and-pinion and direct linear-motor drives reveals that the target performances can only be achieved with linear-motor drives. The linear-motor solution yields also better accuracy and better repeatability and a higher bandwidth of the servo system. Further analysis are necessary to study the effect of cogging, of the very high attraction forces, of the thermal effects, etc.

5. A general, "decoupled" method has been derived to optimise the motor-transmission unit in a traditional rotary-motor feeddrive system.

6. Three representative test set-ups have been developed and built: one rotary motor/ball screw combination driving a slide on roller guideways, one linear-motor axis with slides on roller guideways and one linear-motor axis with slide on air bearings. These test beds were extremely useful throughout the project to validate the many concepts and methods that were developed.

7. Reliable dynamic identification schemes have been developed and applied to the test set-ups. This identification step is very important to derive accurate control models.

8. A generic control scheme has been developed and applied to the test set-ups as well as to an existing machine. The control scheme is based on state feedback and a disturbance observer for disturbance rejection and a feedforward scheme for tracking error minimisation. A special feedforward scheme for force ripple compensation in the linear-motor system has been added.

9. A preliminary design of a 10,000 N linear motor has been made to assess the feasibility of its use in the case studies put forward by COMAU.

10. A generic W-structure for very high-speed milling has been proposed.

11. The generic control scheme has been implemented on an existing high-speed milling machine, making use of the existing controller. The results were rather spectacular: an average reduction of the tracking errors with a factor 5 have been achieved! Implementation of the complete control scheme is bound to result in even better figures.

12. A "mechatronic compiler" for the design of multi-technological systems has been developed. It allows simulation of the structural behaviour of the system as well as the interaction with the motion controller, and is likely to become a powerful tool in the design of mechatronic systems. It will be further enhanced and completed in the framework of the Kernel II-project.



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References:

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| [1] | Main Task 1, | Sub Task 1.1; | Deliverable: | <i>Functional Units for D. O.A. Machine Tools</i> |
| [2] | Main Task 1, | Sub Task 1.2; | Deliverable: | <i>Machine Tool Functional Analysis and Reference Architecture</i> |
| [3] | Main Task 1, | Sub Task 1.3; | Deliverable: | <i>Report on M.C.U. possible interfaces</i> |
| [4] | Main Task 3, | Sub Task 3.1; | Deliverable: | <i>Applications Characteristic of the Selected Materials</i> |
| [5] | Main Task 3, | Sub Task 3.2; | Deliverable: | <i>Definition of simulation needs</i> |
| [6] | Main Task 3, | Sub Task 3.3; | Deliverable: | <i>Planning solutions and components architectures of the M. C. U.</i> |
| [7] | Main Task 4, | Sub Task 4.1; | Deliverable: | <i>Evacuation of the different techniques used in slideways</i> |
| [8] | Main Task 4, | Sub Task 4.2; | Deliverable: | <i>Investigation into New and Hybrid techniques in slideways and dampers</i> |
| [9] | Main Task 4, | Sub Task 4.3.1; | Deliverable: | <i>Study on active and passive damping systems for rolling element guideways</i> |
| [10] | Main Task 4, | Sub Task 4.3.2; | Deliverable: | <i>Study on the reduction of the stochastic part of friction forces on linear bearings with recirculating rollers</i> |
| [11] | Main Task 4, | Sub Task 4.4; | Deliverable: | <i>identification, modelling, simulation and experimental verification of slideways systems</i> |
| [12] | Main Task 4, | Sub Task 4.5; | Deliverable: | <i>Identification, modelling, simulation and experimental verification of slideways systems</i> |
| [13] | Main Task 5, | Sub Task 5.1.1; | Deliverable: | <i>Technical solutions for motion transmission systems</i> |
| [14] | Main Task 5, | Sub Task 5.1.2; | Deliverable: | <i>Technical solutions for motion transmission systems</i> |
| [15] | Main Task 6, | Sub Task 6.1.1; | Deliverable: | <i>The use of Linear Motor in machine tools</i> |
| [16] | Main Task 6, | Sub Task 6.1.2; | Deliverable: | <i>Rotary Motor and drive design</i> |
| [17] | Main Task 6, | Sub Task 6.2; | Deliverable: | <i>Design of the drive and selection of the optimal drive system components</i> |
| [18] | Main Task 6, | Sub Task 6.3; | Deliverable: | <i>Identification and control of the feed drive behaviour</i> |
| [19] | Main Task 7, | Sub Task 7.1; | Deliverable: | <i>Set of robust control algorithms able to satisfy the motion control requirements of the case studies</i> |
| [20] | Main Task 7, | Sub Task 7.2; | Deliverable: | <i>N. C. controller</i> |
| [21] | Main Task 7, | Sub Task 7.3; | Deliverable: | <i>Test results of the new control algorithms</i> |
| [22] | Main Task 8, | Sub Task | Deliverable: | <i>Design Tools and Methodologies for Motion Unit design. Simulation environment definition and integration of selected tools and methodologies.</i> |
| [23] | Bnte Euram II, Project | | “ <i>KERNEL for advanced Machine Tools</i> ” | Technical Annex |
| [24] | Final Technical Report | | “ <i>The KERNEL book</i> ” | |



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